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Characteristics and Genesis of Preferential Flow Paths in a Piedmont Ultisol

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Numerous methods have been used to characterize the size and abundance of macropores in soils. Few of these studies, however, have attempted to determine what portion of the soil column is involved with water flow or to propose a mechanism by which the preferential flow paths are formed. This study was initiated to describe the abundance and characteristics of preferential flow pathways in a Typic Kanhapudult, commonly found on ridges in the Piedmont region of the southeastern USA and to determine their genesis. Forty 15-cm-diameter columns, 60 cm in length were collected from a conventionally tilled field for identification and evaluation of preferential flow paths. Flow paths were identified using methylene blue dye and the morphology of dye-stained and undyed areas was evaluated. Pore size and abundance for dye-stained and undyed areas were evaluated by image analysis, and fabric of the two areas was described from impregnated blocks and thin sections. Most of the Ap and BA horizons of this soil contributed to flow. Only the lower part of the BA horizon and the Bt horizon had appreciable areas that were undyed, suggesting preferential flow. The dye-stained areas had slightly less clay than undyed areas. Dye-stained areas, however, had about five times more pore area than undyed areas, most of which had pores >0.25-mm equivalent diameter. Common circular morphology of dye-stained areas and the open fabric of soil in these areas with occasional fecal pellets suggest that dye-stained areas in this soil have been biologically modified. The biological modification is attributed to tree roots and burrowing animals during the period of soil development on old and stable landscapes in the region.

Numerous methods have been used to characterize the size and abundance of macropores in soils including (i) water retention curves, (ii) tension infiltrometer measurements (Watson and Luxmoore, 1986; Perroux and White, 1988; Baer et al., 1992), (iii) direct measurement of coarse pores in the field (Ehlers, 1975; Edwards et al., 1988; Logsdon et al., 1990) or on impregnated blocks or thin sections (McBratney and Moran, 1990; Koppi and McBratney, 1991; Singh et al., 1991), and (iv) various radiological methods such as computed tomography and soft x-ray (Warner et al., 1989; Anderson et al., 1990; Bakker and Bronswijk, 1993, Franklin et al., 1994; Mori et al., 1999).

While these methods adequately characterize void size and abundance, they may not yield information concerning void continuity, the contribution of the voids to water flow, or what portion of the soil column is involved with water flow. To overcome this limitation, various dyes have been applied to soils to identify voids contributing to water flow (Bouma et al., 1977, 1979; van Stiphout et al., 1987; Linden and Dixon, 1976; Vepraskas et al., 1991; Shaw et al., 1997, 2000). In addition to quantification of the size and abundance of pores contributing to water flow, dye can be used to guide sampling for characterization of the morphological, physical, and chemical properties of dye-stained and unstained regions within a horizon (Jensen et al., 1998; Noguchi et al., 1999).

Pores or voids contributing to preferential flow are most often considered to be either coarse packing voids between grains or stable aggregates, biological channels, interpedal pores between structural units, or cracks formed as the soil dries (Bouma, 1991; Li and Ghodrati, 1994; Vervoort et al., 1999). Biological pores are most often associated with the activity of earthworms and other fauna in surface horizons (Edwards et al., 1988). In subsoil horizons, pores contributing to preferential flow have been identified as cracks or interpedal pores, although pores attributed to root channels and other biological activity have been reported to depths of 2 m (Bouma et al., 1977, 1979; van Stiphout et al., 1987; Schoeneberger and Amoozegar, 1990; Vepraskas et al., 1991; Williams and Vepraskas, 1994; Shaw et al., 1997). For soils in the Piedmont region of the southeastern USA, several studies have reported preferential flow through near-surface soil horizons (Quisenberry et al., 1993; Nortcliff et al., 1994; Gupte et al., 1996). Few of these studies, however, have attempted to determine the characteristics and origin of the pathways of preferential flow. Thus, this study was initiated with the following objectives: (i) to describe the characteristics of preferential flow paths in the upper horizons of a common soil in the Piedmont region of the southeastern USA, and (ii) to ascertain the genesis of these preferential flow pathways.

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MATERIALS AND METHODS

Forty 15-cm-diameter columns were collected with a tractor-mounted hydraulic probe from a 20- by 30-m area of a nearly level (1% slope) Cecil map unit (fine, kaolinitic, thermic Typic Kanhapludult) on a broad ridge in the Southern Piedmont region of the southeastern U.S, Piedmont near Watkinsville, GA (33°52′ N, 83°27′ W). The area sampled had been in conventionally tilled row crops for at least 10 yr before sampling. The intended sampling depth was 60 cm, but probe refusal resulted in column lengths that ranged from 30 to 60 cm. Horizons included in the sampling were the Ap, BA, and the upper part of the Bt. The boundary between the Ap and BA horizons was relatively uniform and ranged from 17 to 21 cm. The boundary between the BA and Bt horizons ranged from 35 to 45 cm and was gradual and wavy.

In the laboratory, each column was mounted on a sand-filled 15-cm i.d. polyvinyl chloride (PVC) cap with a hole in the bottom and coated with liquid saran using a paint brush. A sheet-metal cylinder, the diameter of the outside of the PVC cap, was placed over the column and liquid paraffin was pored into the space between the soil column and the sheet-metal cylinder (about 1 cm) to encase the column in paraffin. This was done to prevent side wall flow and to provide rigidity for subsequent handling. After slowly saturating the columns from the bottom with 0.025 *M* KNO_3 to prevent clay dispersion and for measurement of Br^- breakthrough curves (Gupte et al., 1996), a 1 g L^{-1} solution of methylene blue was leached through the columns under constant head to stain preferential flow paths. The methylene blue solution was leached through the columns until complete breakthrough had been accomplished, as indicated by spectrophotometric measurement of inflow and outflow dye concentrations. Complete breakthrough of methylene blue dye solution indicated that almost all "old" water in areas of the column contributing to flow had been replaced by the methylene blue dye solution, thereby identifying the soil areas where water was moving through the column (Bouma, 1991). Methylene blue is cationic and is adsorbed to negatively charged sites in the soil. Thus, 30 to 40 pore volumes of dye solution, applied over 1.8 to 8.5 d, were required to ensure that water-conducting pores in the lower part of the columns had been stained.

The large volume and associated long contact time required for complete breakthrough of the methylene blue solution raised concern that nonconductive areas in the upper part of the columns might be stained by methylene blue because of redistribution of the dye. The columns were saturated at the time the methylene blue solution was introduced, however, and diffusion was the only mechanism that would result in staining of nonconductive areas of the columns. Because methylene blue is cationic, diffusion into fine matrix pores would be relatively slow. Observations of nonconductive B horizon fragments in the Ap horizon and dye staining along open conductive voids in deeper horizons suggested the dye had penetrated into nonconductive areas about 1 to 3 mm. Thus, aggregates or peds <3- to 4-mm diameter would be expected to be completely dye stained even if interior portions of these peds were not contributing to water flow. Division of the columns into shorter individual horizons would have helped to minimize dye redistribution, but because of other objectives in the study (Gupte et al., 1996), division of the columns was not possible.

After dye staining, the columns were allowed to drain and were sliced horizontally at 5-cm intervals with a fine-toothed saw. The upper surface of each slice was carefully picked with a dissecting scalpel to remove smearing caused by the slicing and to reveal as much of the natural soil structure as possible. The area that had been dye stained was measured for the central 10- by 10-cm section of each column segment by image analysis. Camera magnification and screen resolution for this analysis resulted in a pixel size of about 0.05 by 0.05 mm. Individual dye-stained areas <2 pixels were removed before analysis. Thus, the minimum size of dye-stained areas included in this analysis was about 0.10-mm equivalent diameter. For our purposes, the terms *pore area* and *dyed-stained area* are equivalent and will be used when discussing stained areas observed in a cross section.

Bulk sample and undisturbed clods were collected from dye-stained and undyed areas of selected column segments. Clods were dried and impregnated with thermal epoxy containing 0.03% (w/w) fluorescent additive. Polished blocks and thin sections were prepared by standard techniques (Murthy, 1986). Area of pores in dye-stained and undyed regions on the polished surface of the blocks was measured by image analysis under ultraviolet light. Field of view for this analysis was about 4 by 4 mm, and minimum pore size resolved under analysis conditions was about 0.05-mm equivalent diameter. Thus, pores with equivalent diameters <0.05 and >4 mm were excluded from the analysis. Samples from each 5-cm segment and samples from selected dye-stained and undyed regions were treated with 30% H_2O_2 to remove the methylene blue dye, and particle-size distribution was determined by pipette and sieving (Kilmer and Alexander, 1949).

RESULTS AND DISCUSSION

Dye-Stained Area

The dye-stained area throughout the length of the columns was >60% (Fig. 1). At each depth, the number of columns on which dyed area and clay content was measured is shown at the left of the figure. Because of hydraulic probe refusal during sampling and the resulting variation in column length, the number of columns analyzed decreased below 35 cm. Fracture of columns during transport, especially the friable upper part of the Ap horizon, also decreased the number of columns analyzed from the 40 originally sampled. In Ap and BA horizons, dye-stained area was >95% (Fig. 1), indicating that most of the volume of these horizons was transmitting water. The Ap horizon had a sandy loam texture, weak structure, and pores that

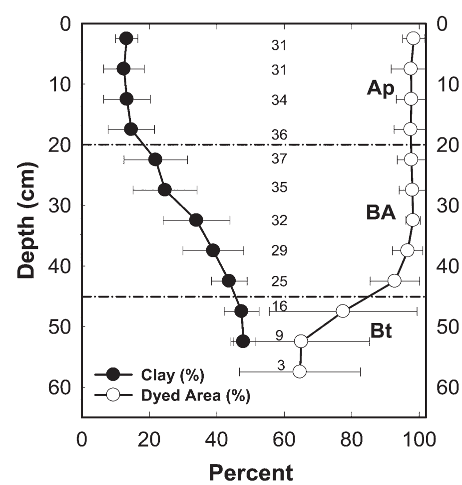

Fig. 1. Depth distribution of mean clay content and dyed-stained area. The number associated with each depth is the number of columns contributing to the mean. The error bar represents one standard error of the mean. Horizon boundaries indicated on the figure represent typical depths found in the Piedmont region of the southeastern USA.

were dominantly coarse packing voids between grains. Few coarse pores or open channels were observed in the field. The only regions not stained by dye in the Ap horizon were 10- to 50-mm-diameter fragments of BA or Bt horizon that had been incorporated by tillage (Fig. 2A). These undyed fragments were not contiguous from top to bottom of the 5-cm slice.

The dye-stained area remained high and relatively constant through the BA horizon (Fig. 1), suggesting that there was little preferential flow within this horizon or that there was little impediment to flow in this horizon. As in the Ap horizon, undyed areas in the BA horizon were zones with morphology similar to the subjacent Bt horizon (Fig. 2B). The undyed zones in the BA horizon may be fragments of Bt horizon incorporated by deep tillage. The depth that these undyed regions become common, however, is beyond most tillage operations in these soils and the undyed regions often tended to be contiguous from top to bottom of the 5-cm slice, suggesting remnant fingers of the Bt. Additionally, distinct differences in color and texture that might suggest mixing by tillage were not observed in the BA horizon in the field.

In the lower part of the BA horizon, undyed regions increased in size, and these undyed regions often contained circular to elliptical dye-stained zones (Fig. 2C). The circular morphology of dye-stained areas within relatively large undyed areas suggests that these water-conductive zones were formed by roots or burrowing organisms, and that modification of the soil fabric associated with rooting and burrowing contributed to the soil's ability in these zones to transmit water.

Dye-stained area in the Bt horizon tended to be less than overlying horizons (Fig. 1). The dye-stained area in the Bt horizons was not significantly lower than that in overlying A and BA horizons, but the hydraulic probe was not able to penetrate into the Bt horizon at all sample locations. Thus, this horiz on had fewer evaluations of dyed area than overlying horizons, which increased variation about the mean. In addition, the boundary between the BA and Bt horizons was gradual and wavy. Thus, part of the column segments identified by depth as being part of the Bt horizon may have been better placed as part of the overlying BA horizon.

There were no macroscopically observable differences in color, texture, or structure between dyed and undyed areas. Dye-stained areas in the Bt horizon had irregular, circular, or elongate morphology (Fig. 2D). The horizon was described as having a moderate, fine subangular blocky structure, and the linear dye-stained areas were attributed to water flow along structural faces. The linear dye-stained areas, however, were longer than the ped faces of the fine structure described in this horizon and were interpreted as being associated with a very weakly expressed, coarser, secondary structure common in soils in this area (Quisenberry et al., 1993; Nortcliff et al., 1994). The circular dye-stained regions were 5 to 20 mm in diameter, and their circular or tubular morphology suggests a biologic origin as coarse, infilled channels originally formed by roots and burrowing organisms.

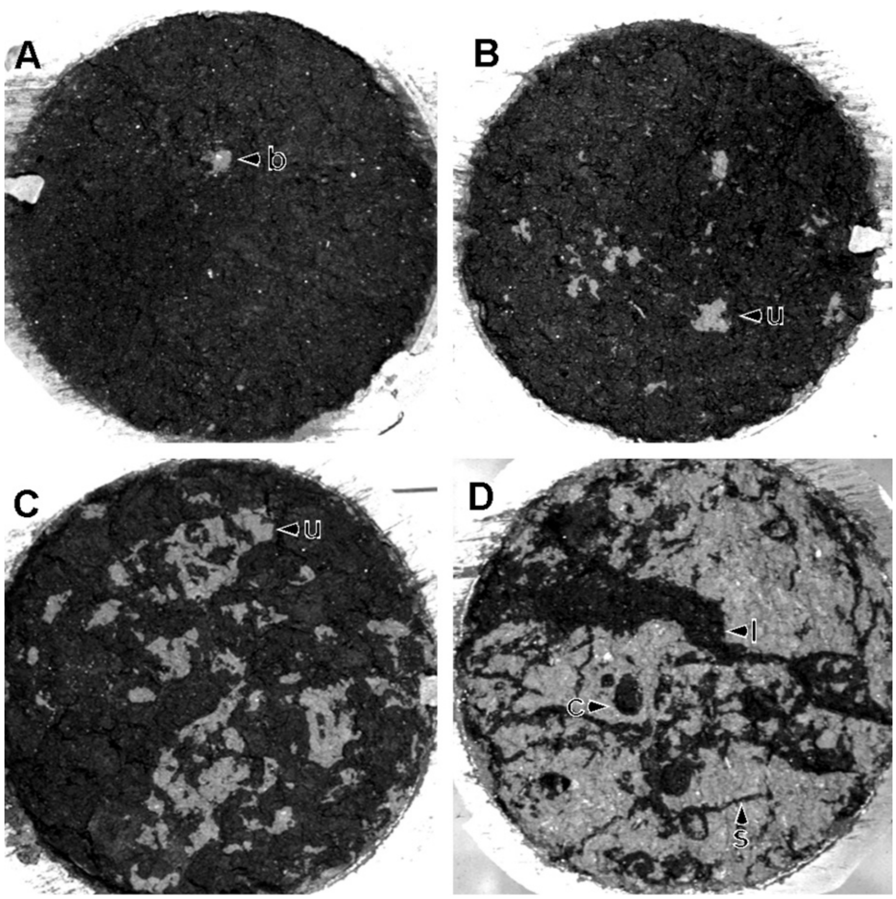

Fig. 2. Horizontal faces of column slices: (A) Ap horizon at 10 cm, (B) BA horizon at 20 cm, (C) BA horizon at 35 cm, and (D) Bt horizon at 55 cm; b = undyed B horizon fragment, u = undyed areas, c = circular dyed area, l = thick elongate dyed area, s = linear dyed area assumed to be associated with a structural face. Column diameter was 15 cm.

Clay Content of Dye-Stained and Undyed Soil

The dyed areas of the Ap horizon had less clay than underlying horizons, and the clay content of the upper BA horizon was slightly less but not statistically different from that in the lower BA and Bt horizons (Fig. 3). The clay content of the undyed material in all horizons was similar (Fig. 3). The relatively high clay content of undyed material in the Ap horizon supports the conclusion that undyed regions in this horizon were fragments of B horizon incorporated by tillage.

The difference in clay content between dyed and undyed material was greatest in the Ap horizon (7.5 vs. 33.3% clay for dye-stained and undyed regions, respectively; Fig. 3). In the upper BA horizon, dye-stained soil had about 15% less clay than undyed soil (Fig. 3). Because of the scarcity of undyed material in the Ap and upper BA horizons in areas of sufficient size to allow them to be sampled separately from dyed material, differences in clay content of dyed and undyed material in these horizons could not be statistically analyzed. Dyed area was >90% throughout the Ap and BA horizons even though the clay content of the dyed material in the BA horizon was appreciably greater than that in the Ap horizon (Fig. 1 and 3). This suggests that although clay increased in the BA horizon, most of the area (volume) of this horizon, especially the upper part of the horizon, had fabric and pore-size distribution that were favorable for water movement. In the lower BA and Bt horizons, dye-stained regions had slightly less clay than undyed regions, but this difference was not significant (Fig. 3). The similarity in clay content between dyed and undyed material suggests that fabric and pore-size distribution in dyed areas was different from that in undyed parts of the soil and was favorable for water movement. Because the dyed areas in the Bt horizons had more clay than the Ap horizon, the origin of these zones cannot be attributed solely to infilling of material from the overlying Ap horizon.

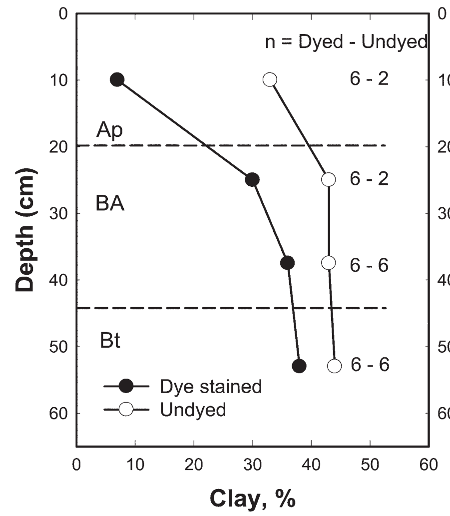

Fig. 3. Clay percentage in dye-stained and undyed soil. The numbers beside each pair of points represent the number of samples contributing to the mean from dyed and undyed areas within a specific depth range. The mean at 10 cm represents samples from various slice depths within the Ap horizon. Means at lower depths represent samples from slice depths from a 15-cm depth increment. The error bar represents one standard error of the mean. Horizon boundaries indicated on the figure represent typical depths found in the Piedmont region of the southeastern USA.

Porosity and Microfabric of Dye-Stained and Undyed Soil

As measured by image analysis on polished blocks, dye-stained areas had a significantly greater percentage of pores >0.10-mm equivalent diameter than undyed areas (14.9% compared with 2.7%; Fig. 4). The data in Fig. 4 are means for samples from all depths within the columns, but the magnitude of the difference in porosity was consistent with depth (data not shown).

The greatest difference in pore area was for the coarser pore-size ranges (Fig. 4). For pores with equivalent diameters between 0.10 and 0.25 mm, dyed-stained areas had about twice the pore area as undyed areas (1.1 vs. 2.5%). For pores with equivalent diameter >0.25 mm, this difference was even greater, with dye-stained areas having a pore area of about 12% compared with a pore area of 2% for undyed areas (Fig. 4).

The greater area and larger size of pores in dye-stained regions suggest that pore size and abundance have a strong influence on dye movement and implied paths of water movement through these soil columns. A lack of macropores in undyed regions is apparently restricting movement of dye and water. The size and number of macropores have been reported to be the major factor influencing saturated hydraulic conductivity of horizons in soils from the Piedmont and Coastal Plain of the southeast USA (O'Brien and Buol, 1984; Southard and Buol, 1988; Shaw et al., 1997).

It should be noted that the entire soil matrix in dyed regions may not be conducting water. Because of abundant porosity in dye-stained regions, diffusion of the methylene blue may have resulted in complete staining of aggregates and peds <3- to 4-mm diameter although the interiors of the small peds were not conducting water. Because of differences in pore area and size between dye-stained and undyed regions, dye staining effectively separated areas of the soil that were transmitting water from those that contribute little to water movement through the profile.

Pores in the Ap horizon were dominantly simple and compound packing voids resulting from packing of 0.1- to 1-mm-diameter aggregates and grains (Fig. 5A). Few coarse channels were observed, as would be expected for a horizon that had been tilled within the year before sampling. In dye-stained regions of the BA horizon, compound packing voids were common (Fig. 5B). These voids were coarser than those in the Ap horizons because the peds forming the voids were coarser (1–5-mm diameter) than the sand grains forming packing voids in the Ap horizon. One- to three-millimeter-diameter channels were commonly observed in dye-stained regions of the BA horizon (Fig. 5B). Also evident in the BA horizon were coarse (2–8-mm-diameter) open or partially infilled channels (Fig. 5C). The infilling material was dominantly open-packed microaggregrates that often had morphology suggestive of fecal pellets (Fig. 5C). The microfabric of undyed regions was a dense matrix with few voids (Fig. 5D). Peds and intrapedal pores were generally absent and few channels were present.

Dye-stained regions in the Bt horizon had two morphologies. The first accounted for most of the dye-stained area and consisted of coarse (1- to >10-mm-diameter) channels similar to those observed in the BA horizon (Fig. 6A and 6B). The smaller diameter channels were often open, but the coarser channels were commonly partially or totally infilled (Fig. 6A, 6B, and 6C). The material infilling the coarse channels was weakly pedal, and like

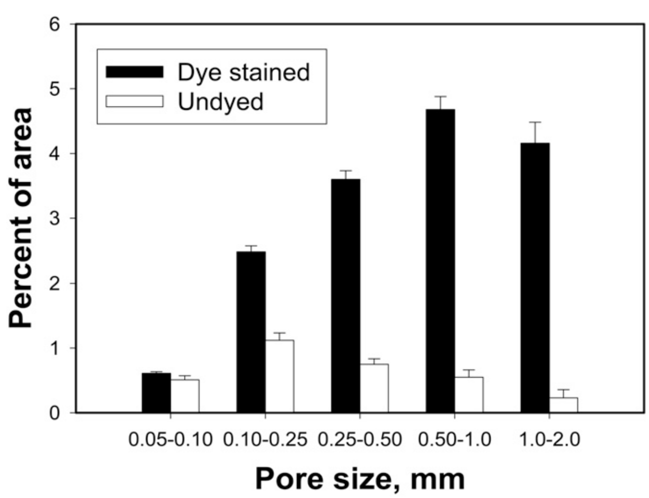

Fig. 4. Size distribution of mean pore area for dye-stained and undyed soil as determined by image analysis. Means represent samples from all column depths, *n* for dye-stained material = 52; *n* for undyed material = 27. The error bar represents one standard error of the mean.

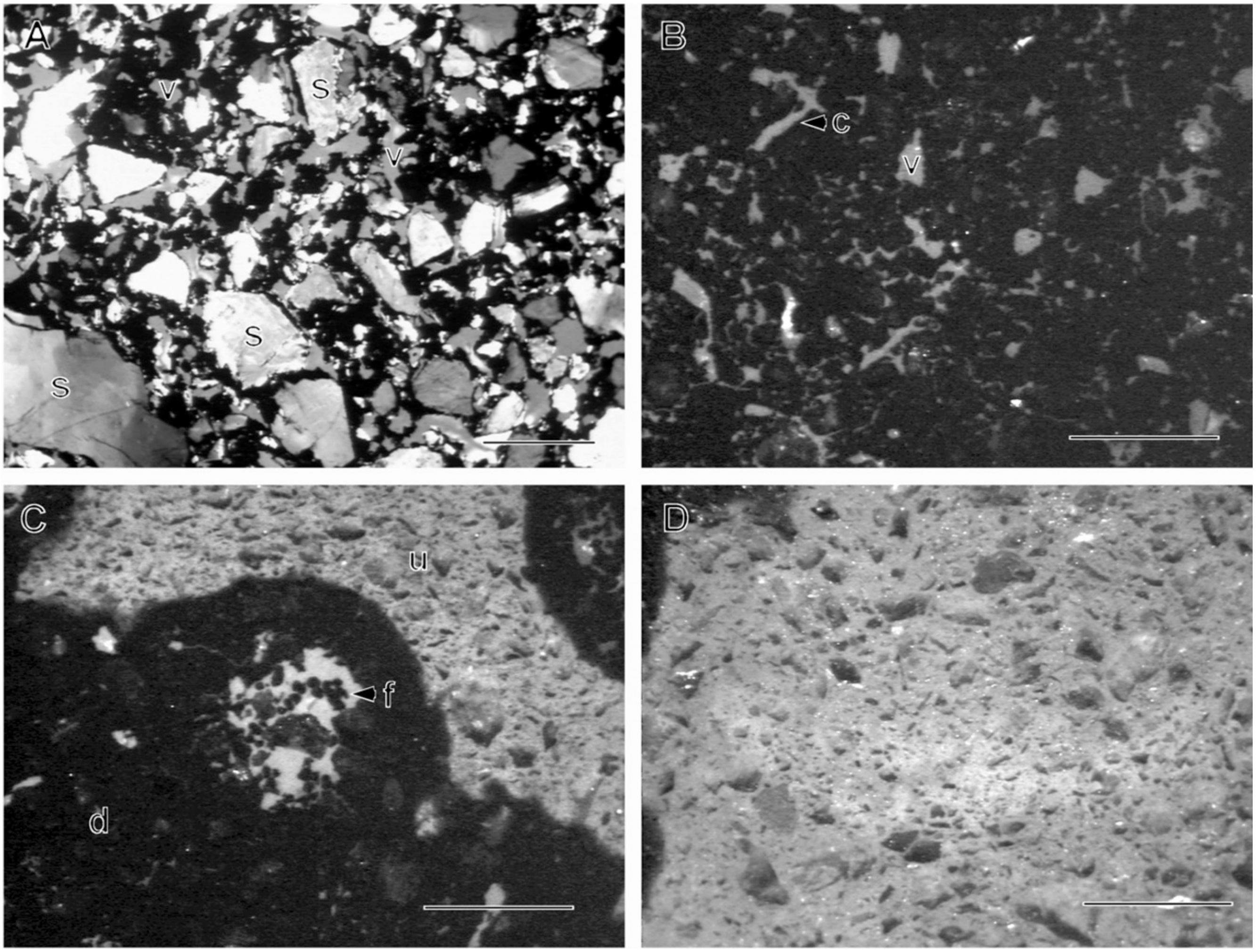

Fig. 5. Micrographs of dye-stained and undyed soil from Ap and BA horizons: (A) thin section, under partially polarized light, of Ap horizon at 6 cm, (B) polished block of dye-stained soil from BA horizon at 37 cm, (C) polished block of BA horizon at 28 cm showing fecal pellets (arrow), and (D) polished block of undyed soil from BA horizon at 28 cm; c = channel, d = dye-stained soil, s = sand grain, u = undyed soil, v = void. Bar length = 5 mm.

that observed in the BA horizon, the material commonly had a morphology suggestive of a biological origin.

The second dyed morphology in Bt horizons was thin elongate regions associated with narrow interpedal voids (structural faces). The total area of this dye-stained morphology was less than that of the nonstructural morphology described above, and thus probably accounts for a smaller portion of the total water movement through this horizon. Structural units were recognizable in undyed regions of the Bt horizon (Fig. 6D), but most interpedal pores were plugged by translocated clay (origin of clay confirmed in thin sections that are not shown). The translocated clay is apparently restricting water and dye movement along structural units, as has been reported for deeper, less clayey horizons from Piedmont soils (Williams and Vepraskas, 1994).

Genesis of Preferential Flow Regions

The pattern of dye staining and microfabric of dye-stained regions in the A, BA, and upper Bt horizons of this soil suggests that movement of water and dye was primarily through regions that have been influenced by biological activity. Landscapes on which this and similar soils have developed are old and stable. Before European settlement and clearing of the land for agricultural enterprises, the landscapes were predominantly forested. Thus, coarse tree roots would have been expected to permeate the upper horizons of the soil. In addition, relatively high populations of earthworms, insects, and other burrowing organisms would have been expected to be present under the forest canopy before clearing.

Invasion by coarse roots and the action of burrowing organisms would have created open channels in upper B horizons of the soil that have been subsequently partially infilled with coarser textured soil from overlying sandy horizons. These coarser textured zones in the soil would be expected to be the preferred zones for subsequent rooting and biological activity. With time, greater volumes of soil would be explored by roots and burrowing organisms and the volume of soil modified by roots and burrowing organisms would increase. Coarse-textured material infilling channels would become mixed with more clayey material in the surrounding soil matrix. Thus, while clay content of these regions would not be appreciably less than that of the matrix, the mixing of the soil would result in regions with a more open fabric and with more large pores than the unmodified matrix of the horizon. The abundance of coarse pores would result in more rapid movement of water and solutes through these zones than would be observed in the undisrupted soil.

A conceptual representation of the relationship between biologically modified and unmodified regions in upper hori-

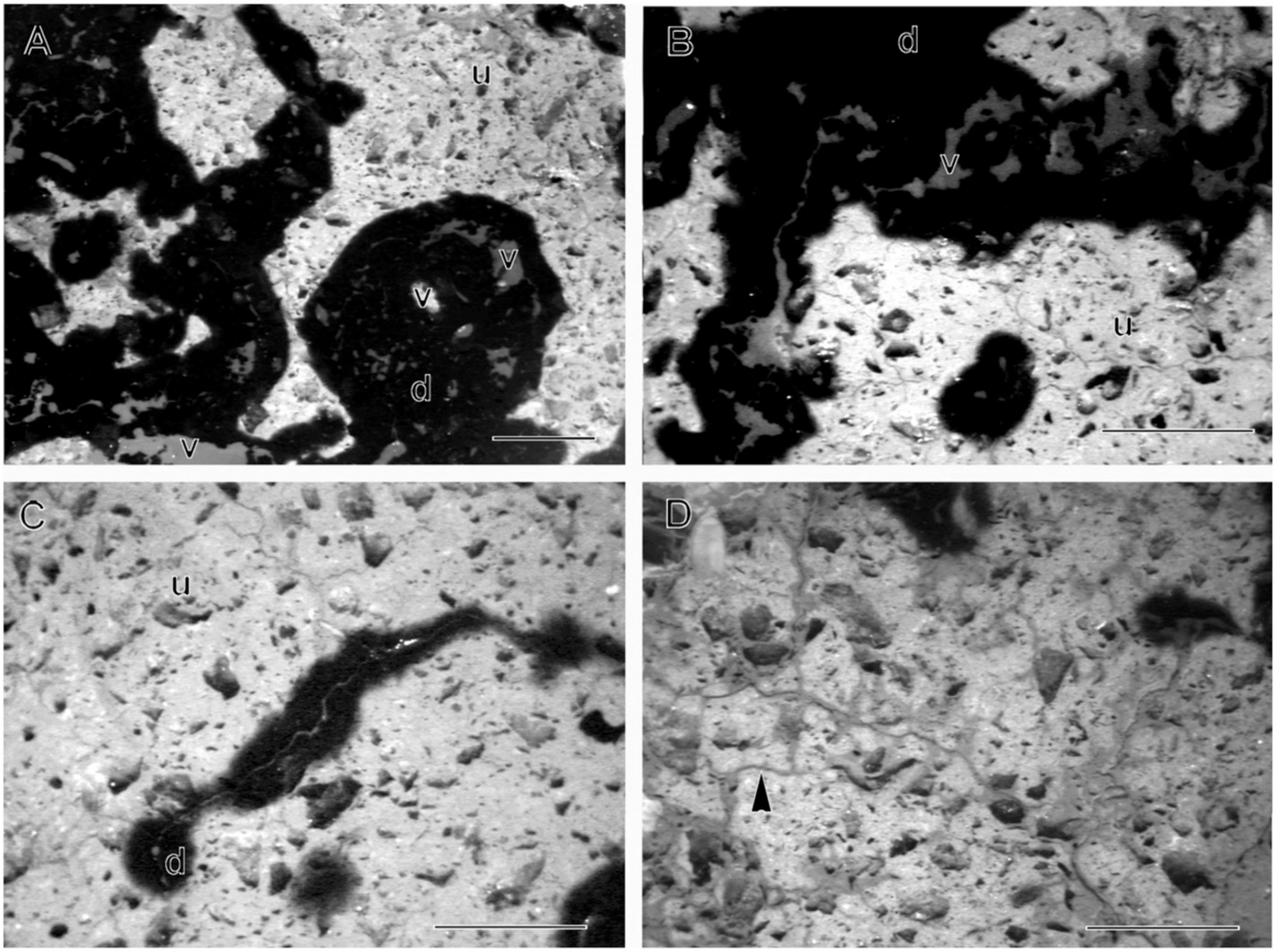

Fig. 6. Micrographs of polished blocks from Bt horizon: (A) 50-cm depth, (B) 55-cm depth, (C) 48-cm depth, and (D) undyed soil at 55-cm depth showing structural voids plugged with clay and Fe oxides (arrow); d = dye-stained soil, u = undyed soil, f = fecal material, v = voids. Bar length = 5 mm.

zons of this soil is presented in Fig. 7. The BA horizon has been almost entirely modified by biological activity, and as a result the bulk of the horizon has coarse porosity and would be expected to contribute to water and solute movement. The gradual increase in clay in this horizon may be explained by greater biological activity in the upper part of the horizon, with associated mixing of coarser textured surface soil material. With depth, less coarse-textured material has been added by pore infilling and the soil is more clayey.

In the lower part of the BA horizon and deeper horizons (Bt horizon and below), biological activity has been less, and these horizons have a proportion of material that has not been biologically altered. Because of translocation of clay and other mobile constituents and volume changes associated with soil development, the unaltered material lacks coarse porosity that contributes to rapid movement of water and solutes through the horizon. Most movement of water and solutes in these horizons is through zones that have coarser and more abundant pores that have resulted from biologic modification. The biological alteration was probably the result of deep tree roots and subsequent actions of various microflora and fauna inhabiting the root channels.

CONCLUSIONS

Dye staining indicates that most movement of water and solutes through the A and BA horizons of a soil common in the Piedmont region of the southeastern USA occurs through the soil matrix when the land has been conventionally tilled. Only a few areas, morphologically similar to subjacent nonconductive areas of underlying Bt horizons, do not contribute to flow. In the lower part of the BA horizon and Bt horizons, evidence of preferential flow is more common. While dye-stained areas in these horizons tended to have slightly less clay than undyed regions, this difference did not appear to be a major factor contributing to flow differences. Dye-stained regions had about five times more pore area than undyed regions, and this difference in porosity appears to be the major factor contributing to preferential flow through these horizons.

Gross morphology of many of the dye-stained areas and the fabric of the soil in these regions suggest that the soil in these areas has been modified by biological activity. Biologically modified areas have a porous, open fabric through which water and solutes are more prone to move through than unmodified zones where structural voids have been plugged by clay and Fe oxides. Landscapes in this region are old and stable. Thus, during the period of soil development, invasion of the soil by tree roots and the activity of burrowing organisms have resulted in

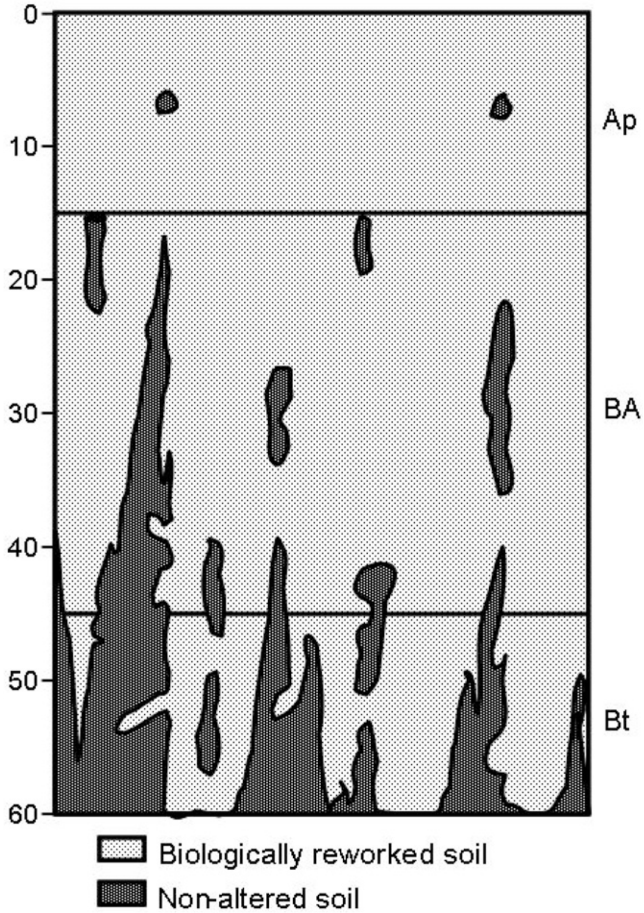

Fig. 7. Schematic representation of biologic modification of soils in this study. Horizon boundaries indicated on the figure represent typical depths found in the Piedmont region of the southeastern USA.

considerable modification of the soil. This biological modification appears to be a major factor influencing preferential movement of water and solutes through these soils.

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